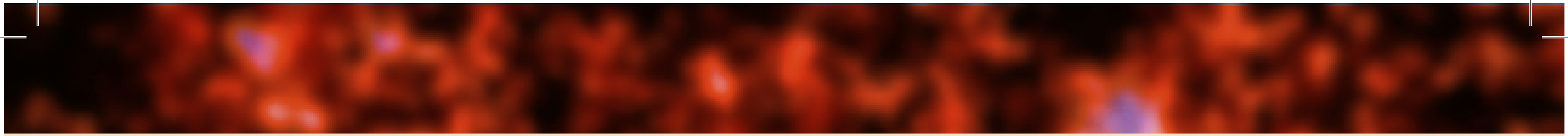
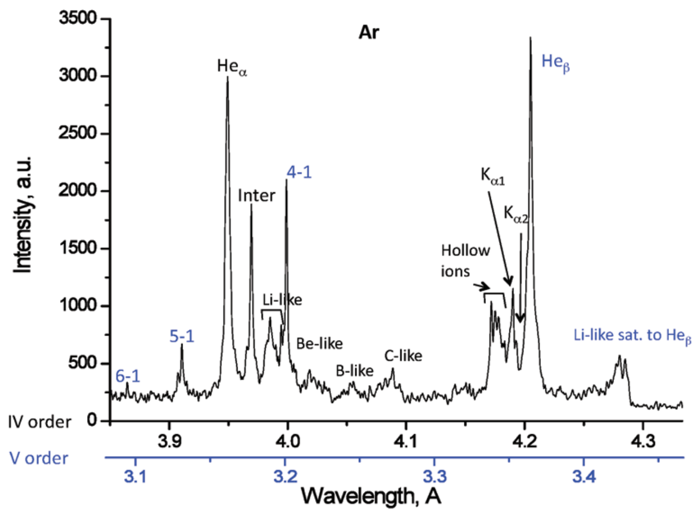


Spectral Features of the Inner Shell X-ray Emission Produced by High Contrast Laser Irradiation of Argon Clusters

James Colgan, Joseph Abdallah, T-1

We report on a joint theoretical and experimental study of the X-ray emission from ultrashort laser pulse irradiation of argon cluster targets. Experiments have been performed using the Japanese J-KAREN laser, with large argon cluster sizes and very high laser contrasts, which have allowed clear and unambiguous observation of exotic inner-shell transitions in near-neutral argon ions—so-called "hollow-atom" transitions. The interaction of the main laser pulse with the unperturbed target is a necessary requirement for observing these lines. Our measurements are supported by kinetics calculations using the LANL ATOMIC code, in which a very detailed atomic model is used. The calculations predict all of the spectral features found experimentally, and support the notion that the X-ray emission arises from many ion stages of the argon plasma, from near-neutral through He-like ions, and from a range of plasma temperatures and densities.

Fig. 1. Measured emission spectra from IV and V order mica crystal obtained from an argon cluster target, obtained using a laser contrast of 10^{-10}. The V order transitions are labeled in blue font and correspond to the lower (blue) wavelength axis. The IV order transitions are labeled in black font and correspond to the upper (black) wavelength axis.



A recent joint theoretical and experimental study has been made of the X-ray emission from ultrashort laser pulse irradiation of argon cluster targets. The experiments were performed using the Japanese J-KAREN laser with a high laser irradiance and very high contrast (10^{-10}) of prepulse to the main pulse. The theoretical modeling was performed by James Colgan and Joseph Abdallah using the ATOMIC plasma kinetics code. This work has been submitted for publication [1].

The experimental investigations focused on two X-ray wavelength regions near the He$_\alpha$ and He$_\beta$ emission lines of argon. The very high resolution of the experiment allowed clear identification of the He$_\alpha$, intercombination, and a number of Li-like satellites (see Fig. 1). However, a number of other prominent features were observed at slightly longer wavelengths, which were thought to arise from deep inner-shell (K$_\alpha$) emission of near-neutral argon, so-called "hollow atom" emission lines.

To test this hypothesis, a very detailed atomic physics model was constructed of all ions of argon. A set of detailed-level structure and collision calculations were made for C-like argon through the bare ion using the LANL atomic physics codes, including full configuration-interaction among all levels [2]. This model included over 23,000 levels and was then used to solve the collisional-radiative equations using the ATOMIC code [3], resulting in various plasma properties, including the ionization balance, energy losses, and the emission spectrum of argon. A second set of calculations was also made for all ion stages of argon, in which a large number of configurations were retained, including configurations where one or two electrons are removed from the K and/or L shell of all ion stages, as appropriate. The collisional radiative equations were solved at the configuration-average approximation, and a mixed unresolved transition array (MUTA) [4] approach was used to obtain a more detailed level-to-level spectral description of the strongest lines in the plasma, even though the ionic populations were obtained through a configuration-average description. All kinetics calculations were made in steady state and assuming an optically thin plasma. A small fraction (around 1%) of hot electrons was also included in the modeling.

A comparison of the measured emission spectrum and the ATOMIC modeling calculations is shown in Fig. 2. In each panel, the measurements are compared to ATOMIC calculations made at various plasma temperatures and densities, as indicated. We find that hot, moderately dense plasma (upper-left panel) describes quite well the resonance features arising from He-like argon. Calculations at lower temperatures and larger densities then provide emission from lower-

For more information contact James Colgan at jcolgan@lanl.gov.

charged-ion stages of argon (upper-right and lower-left panels). Finally, calculations at quite cold (around 10 eV) and dense conditions find emission near 4.18 Å, which matches the experimental features in this region very well. These emission features are found to be the result of *2p→1s* transitions in neutral and near-neutral argon, in which several electrons have been excited to the *3d* or *n=4,5* shells. These features have previously been labeled hollow atom transitions.

Our calculations and measurements lead us to the following picture of the laser-cluster interaction. The large size of the clusters (around 1.5 µm) and the very high laser contrast (10^{-10}) means that a majority of cluster targets remain unperturbed by the laser prepulse by the time the main pulse arrives. The main laser pulse then interacts with a cold and near-solid density argon target. The very high laser intensity (3.5 x 10^{18} W/cm^2) immediately allows electrons to be ionized, which are quickly accelerated to high energies by the laser field (so-called “hot electrons”). These electrons then interact with the neutral/near-neutral argon target, resulting in the hollow-atom emission from the cold, dense plasma. As the laser pulse further ionizes the argon target, the cluster quickly heats up and expands. The hot electrons and other thermal electrons then interact with this expanding plasma, resulting in the observed X-ray emission from more ionized argon ions. Such a scenario clearly implies a highly transient and complicated plasma emission, with observed lines arising from quite different plasma conditions and at quite different times. Preliminary time-dependent calculations also demonstrate that the hollow-atom emission occurs at early times in the plasma expansion, while the He resonance lines are formed at much later (picosecond) times.

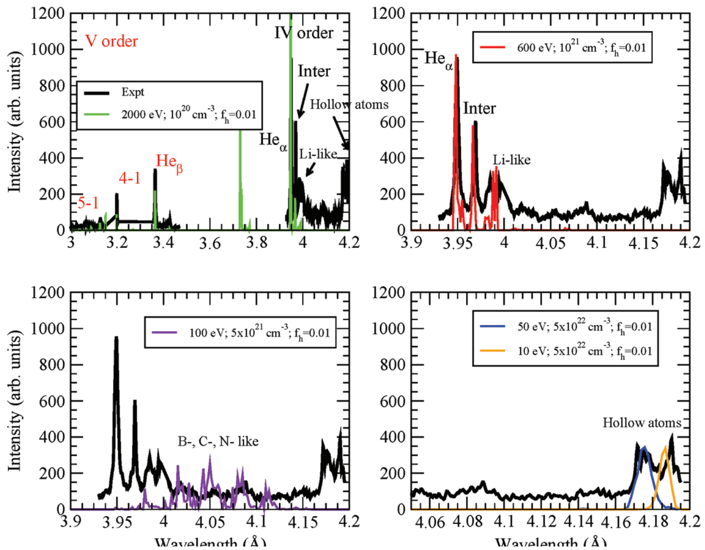


Fig. 2. The upper-left panel shows ATOMIC FS calculations at a temperature of 2000 eV and electron density of 10^{20} cm^{-3} and the upper-right panel shows ATOMIC FS calculations at a temperature of 600 eV and electron density of 10^{21} cm^{-3}. The lower-left panel shows ATOMIC MUTA calculations at a temperature of 100 eV and electron density of 5x10^{21} cm^{-3}, and the lower-right panel shows ATOMIC MUTA calculations at temperatures of 10 and 50 eV and at electron densities of 5x10^{22} cm^{-3}. All calculations include a 1% hot electron component, and are compared to the experimental observations as described in the text.

We emphasize that the modeling of this complicated laser-plasma interaction requires two crucial components: (1) the inclusion of a hot electron fraction in the collisional-radiative modeling, and (2) a sufficiently detailed atomic physics model, in which configurations with one or two electrons removed from the K and/or L shells are included. Without either of these two components, the modeling would not predict the observed hollow-atom features near 4.18 Å.

In conclusion, we have reported on detailed atomic kinetics calculations made to model the complex interaction of an ultrashort intense laser pulse with an argon cluster target. We find that the observed emission results from several different plasma regions, at different times, and at quite distinct plasma conditions. Our calculations demonstrate the ability of the ATOMIC plasma kinetics code to accurately predict plasma properties for laser-produced plasma.

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[3] Magee, N.H., et al., in *14th Topical Conference on Atomic Processes in Plasmas,* New York, Eds J.S. Cohen, S. Mazevet, and D.P. Kilcrease, *AIP Conference Proceedings,* 168 (2004).
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